

# Six-Lepton $Z'$ Resonance at the Large Hadron Collider

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New physics models admit the interesting possibility of a  $Z'$  weak boson associated with an extra  $U(1)$  gauge symmetry and a Higgs boson that is heavy enough to decay into a pair of  $Z$  bosons. Then  $Z'$  production and decay via  $Z' \rightarrow ZH \rightarrow ZZZ$  has a distinctive LHC signal that is nearly background free and reconstructs the  $H$  and  $Z'$  masses and widths. The  $Z'$  decay to 3 pairs of leptons is especially distinctive. The  $ZH$  decay mode exists even if the  $Z'$  is decoupled from leptons, which motivates an independent 6-lepton resonance search regardless of the dilepton search results.

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Many scenarios beyond the standard model (SM) have an extra Abelian  $U(1)'$  gauge symmetry and an associated  $Z'$  weak boson. (For a recent review, see Ref. [1].) If the  $Z'$  has couplings to both quarks and leptons, it will be evident through a resonance in the Drell-Yan subprocess  $q\bar{q} \rightarrow Z' \rightarrow \ell\bar{\ell}$  at hadron colliders [2, 3, 4, 5]. The current Tevatron lower bound on the mass of a  $Z'$  that couples comparably to quarks and leptons is around 800-900 GeV, with the exact bound depending on the model [6, 7]. There is a stringent bound from LEP on the  $Z$ - $Z'$  mixing angle:  $|\alpha_{Z-Z'}| \lesssim 10^{-3}$ . (See Ref. [8] and references therein.) The LEP bound can be satisfied if the  $Z'$  is sufficiently heavy ( $M_{Z'}$  in the TeV range) or the property of the Higgs sector satisfies a certain condition[34].

At the LHC design energy of 14 TeV, the  $Z' \rightarrow e^+e^-$  cross section for some representative models is of order 25 fb for  $M_{Z'} = 1.5$  TeV and 1 fb for  $M_{Z'} = 3$  TeV. (See, e.g., Table 2 of Ref. [9].) With an integrated luminosity of order 1-10 fb<sup>-1</sup> in early LHC running, the clean  $Z'$  dilepton Drell-Yan signal could be the first new physics discovery made at the LHC. However, there exist models in which the  $Z'$  does not have a direct coupling to leptons (e.g., Refs. [10, 11]). For such a leptophobic  $Z'$  the Drell-Yan search is inapplicable, and masses considerably less than 800 GeV are possible. A search for such a  $Z'$  in the dijet channel will be challenging at the LHC [12, 13]. Associated production of a  $Z'$  with the SM  $Z$  boson is an alternative search technique [14]. Our focus in this Letter is on a combined search at the LHC for the  $Z'$  and a

neutral  $CP$ -even Higgs boson ( $H$ ) with mass  $m_H > 2M_Z$ .

The physics of a TeV scale  $U(1)'$  symmetry is intimately intertwined with the Higgs boson sector. (For example, see Ref. [15] to see how the Higgs mass bound changes with  $U(1)'$  in the supersymmetry framework.) Precision electroweak constraints on the Higgs sector can also be relaxed because of mixing between  $SU(2)$  doublet Higgs fields and the  $SU(2)$  singlet fields ( $S$ ) that are introduced to break the  $U(1)'$  gauge symmetry [16].

We consider the  $Z'$  decay to a  $Z$  boson and a Higgs boson with subsequent decay  $H \rightarrow ZZ$ . (See Figure 1.) It does not have to be the only or the lightest Higgs boson. This mode exists even if the  $Z'$  decouples from leptons. The  $Z' \rightarrow ZH$  channel has been studied in the literature [17, 18, 19, 20, 21, 22, 23]. The  $Z'$ - $Z$ - $H$  coupling is model dependent. To estimate its likely size, we consider the case of a single Higgs doublet. Its kinetic term is

$$\begin{aligned} \mathcal{L}_{\text{kin}} &= \left| \left( \partial_\mu - \frac{i}{2} g_Z Z_\mu + i g_{Z'} z[H] Z'_\mu \right) \frac{1}{\sqrt{2}} (H + v) \right|^2 \\ &= -g_Z g_{Z'} z[H] v H Z_\mu Z'^\mu + \dots, \end{aligned} \quad (1)$$

where  $g_Z$ ,  $g_{Z'}$ ,  $z[H]$ , and  $v$  are the coupling constants of the  $Z$ , and  $Z'$ , the  $U(1)'$  charge of the Higgs doublet, and the Higgs vacuum expectation value, respectively. The  $Z'$ - $Z$ - $H$  coupling therefore depends on the  $U(1)'$  charge of the Higgs doublet. More generally, it also depends on mixing of states in the Higgs sector and on kinetic mixing.

In this Letter, we study the feasibility of the LHC to discover the  $Z'$  as well as study the Higgs boson, using this vertex with the leptonic final states only without any missing energy. We take an approach as model independent as possible, and show our results in two simple scenarios for the numerical illustration.

The decays of the Higgs boson are dependent on the Higgs mass and also on any mixing with singlets and other doublets. The relevant  $Z' \rightarrow ZH$  decay modes are  $ZZZ$ ,  $ZW^\pm W^\mp$ , which lead to the final states

$$ZZZ : 6\ell, 4\ell + 2j, 2\ell + 4j, 6j, 4\ell + \text{MET}, \text{ etc.}$$

$$ZWW : 2\ell + 4j, 6j, 4\ell + \text{MET}, \text{ etc.},$$

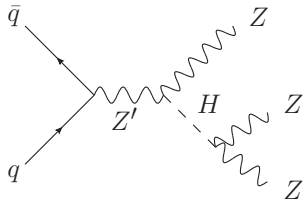


FIG. 1: 6-lepton resonance without direct  $Z'$  coupling to leptons.

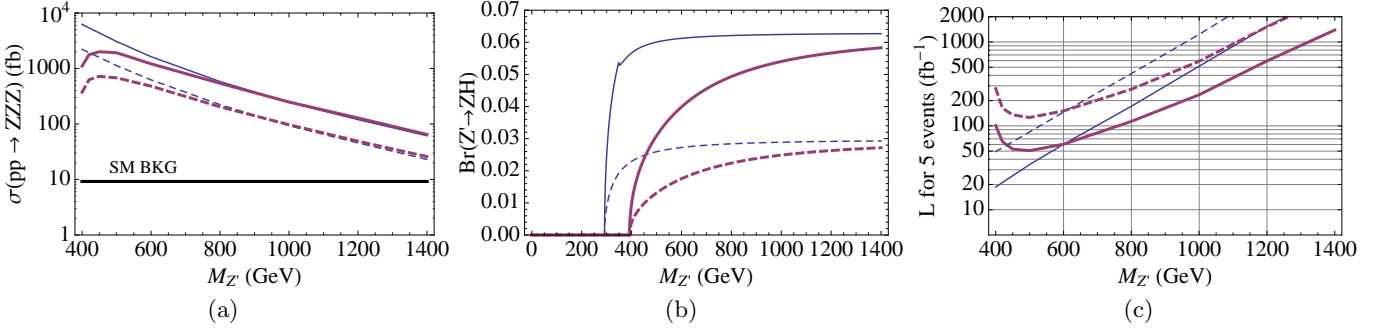


FIG. 2: (a)  $Z' \rightarrow ZH \rightarrow ZZZ$  cross section at the LHC (with  $\sqrt{s} = 14$  TeV). (b)  $Z' \rightarrow ZH$  branching ratio. (c) Required luminosity for five 6-lepton resonance events at the LHC (with  $\sqrt{s} = 14$  TeV). SM-like couplings (dashed) and leptophobic couplings (solid) are assumed with  $m_H = 200$  GeV (thin blue line) and 300 GeV (thick red line).

where MET denotes missing transverse energy carried by neutrinos.

A dramatic  $ZZZ$  signal is 3 pairs of opposite sign same flavor (OSSF) leptons that reconstruct three  $Z$  bosons and then the Higgs boson and the  $Z'$ [35]. Another particularly striking signal is a  $b$ -tagged pair and two pairs of leptons.

When the Higgs is lighter than  $2M_{Z'}$ , either  $H$  or  $Z$  can be off-shell; the event may be produced, but at a greatly reduced rate.

The SM background cross section from  $t$ -channel  $q\bar{q} \rightarrow ZZZ$  is of order 10 fb at 14 TeV [25], which is small compared to the estimated  $Z' \rightarrow ZH \rightarrow ZZZ$  signal. (See Figure 2 (a).) Thus the  $6\ell$  decay mode is essentially free of backgrounds. Since the  $6\ell$  signal is very distinctive, only a few events would already confirm its existence.

The widths of both the  $Z'$  and the Higgs boson can be determined from the invariant mass distributions of fully reconstructed events.

*6-lepton resonance:* Next we simulate the  $Z' \rightarrow ZZZ$  signal at the LHC, implementing typical experimental acceptance cuts and detector simulation. Specifically, we consider the channel

$$q\bar{q} \rightarrow Z' \rightarrow ZH \rightarrow 3Z \rightarrow 6\ell \quad (2)$$

with all intermediate decay particles on shell. The 6-lepton resonance cross section is

$$\sigma_{6\ell} \simeq \sigma(pp \rightarrow Z') \text{Br}(Z' \rightarrow ZH) \text{Br}(H \rightarrow ZZ) \text{Br}(Z \rightarrow \ell\bar{\ell})^3, \quad (3)$$

where the major suppression comes from the triple  $Z$  decay to light leptons,  $\text{Br}(Z \rightarrow \ell\bar{\ell}) = \text{Br}(Z \rightarrow e^+e^-) + \text{Br}(Z \rightarrow \mu^+\mu^-) \simeq 0.067$ .

For a single unmixed Higgs doublet[36], the  $ZH$  partial width is

$$\begin{aligned} \Gamma(Z' \rightarrow ZH) \\ = \frac{g_{Z'}^2 z[H]^2}{48\pi} \lambda^{\frac{1}{2}}(1, x_Z, x_H) \{ \lambda(1, x_Z, x_H) + 12x_Z \} M_{Z'}, \end{aligned} \quad (4)$$

where  $x_Z \equiv (M_Z/M_{Z'})^2$  and  $x_H \equiv (m_H/M_{Z'})^2$ , with  $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$ . Its size can

be comparable to or even larger than the  $e^+e^-$  partial width

$$\Gamma(Z' \rightarrow e^+e^-) = \frac{g_{Z'}^2}{24\pi} (z[e_L]^2 + z[e_R]^2) M_{Z'}. \quad (5)$$

Since the  $ZH$  process does not require any direct coupling between the  $Z'$  and leptons, it may be present even for a leptophobic  $Z'$ [37]. Therefore, a 6-lepton resonance for a leptophobic  $Z'$  is possible.

For numerical illustrations, we use two examples of the  $Z'$  couplings: (i) SM  $Z$  couplings (*SM-like case*), (ii) leptophobic  $Z'$  couplings (*leptophobic case*). The SM-like case assumes  $g_{Z'} = g_Z$ . The leptophobic case adopts  $g_{Z'} = \sqrt{5/3} g \tan \theta_W \simeq 0.46$  and  $z[u_L] = z[d_L] = 1/9$ ,  $z[u_R] = -8/9$ ,  $z[d_R] = 1/9$ ,  $z[H_u] = -1$ ,  $z[H_d] = 0$ , while all leptons have vanishing  $U(1)'$  charges[38].

Though the physical Higgs state depends on mixing among the Higgs doublets and singlets, for illustration we treat the model as effectively having a single Higgs doublet by taking no mixing and  $v_u = v \simeq 246$  GeV[39]. Multiple Higgses would lower the event rates and the dilution would depend on details of the Higgs sector. Numerical results with our treatment will serve as the upper bound on the size of the signal.

Figure 2 (a) shows  $\sigma(pp \rightarrow Z' \rightarrow ZZZ)$  at the LHC for  $m_H = 200$  and 300 GeV in both models, and Figure 2 (b) shows  $\text{Br}(Z' \rightarrow ZH)$ . (There can also be a  $Z' \rightarrow WW$  mode due to the  $Z$ - $Z'$  mixing.) Larger  $M_{Z'}$  would provide larger  $\text{Br}(Z' \rightarrow ZH)$  for a given  $m_H$ , but the  $Z'$  production cross section would be smaller. Larger  $m_H$  would decrease  $\text{Br}(Z' \rightarrow ZH)$  but increase  $\text{Br}(H \rightarrow ZZ)$ .

The total decay widths are roughly  $\Gamma_{Z'} \sim 0.03M_{Z'}$  (SM-like case) and  $\Gamma_{Z'} \sim 0.02M_{Z'}$  (leptophobic case). The leptophobic case has a larger  $\text{Br}(Z' \rightarrow ZH)$  than the SM-like case because of the relatively large  $z[H]$ .

The  $ZH$  decay requires a nonzero  $U(1)'$  charge for the Higgs doublet. A purely leptophobic model with a single Higgs with  $z[H] \neq 0$  would not allow lepton Yukawa couplings. However, this shortcoming can be overcome in multidoublet models (as in our leptophobic case example)[40].

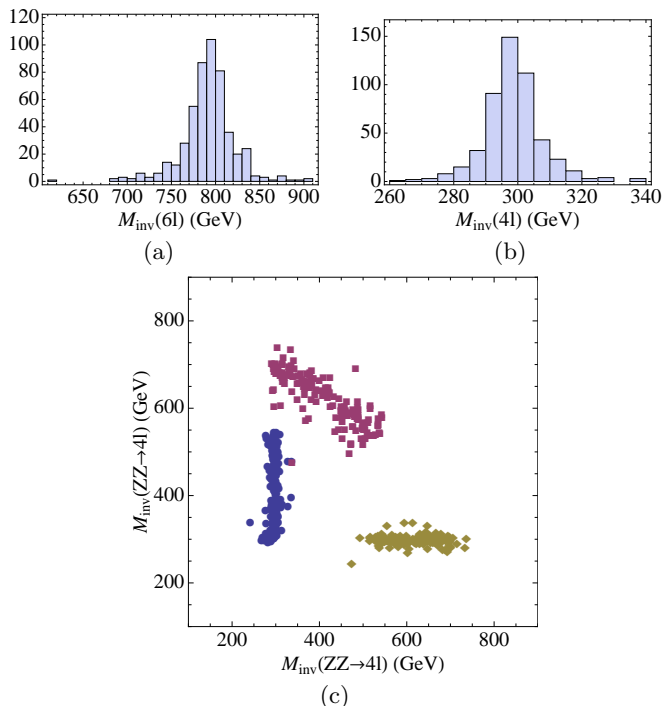


FIG. 3: Reconstruction of the  $Z'$  and Higgs boson for  $M_{Z'} = 800$  GeV,  $\Gamma_{Z'} = 16.6$  GeV,  $m_H = 300$  GeV and leptophobic couplings. (a) 6 leptons around the  $Z'$  mass. (b) 4 leptons around the Higgs mass. (c) Dalitz plot revealing the Higgs mass. The axes are 2 possible reconstructions for the  $m_{\text{inv}}(4\ell)$ . There are 3 combinations of 2 pairs of  $ZZ$ . These 3 combinations are sorted and plotted together in {lightest, middle} (blue circle), {middle, heaviest} (red box), and {heaviest, lightest} (yellow diamond).

*Analysis:* For numerical analysis, we use **MadGraph** (Ver. 4.4.15), which adopts **Pythia** and **PGS** for hadronization and detector simulation[41] [30]. We use **CTEQ6L** for parton distribution functions [31], and take  $M_{Z'}$  for the factorization scale.

$\text{Br}(Z' \rightarrow ZH)$  and  $\text{Br}(H \rightarrow ZZ)$  depend on the details of the model, including the couplings of the Higgs, leptons, and possible exotic fields. We illustrate using the two examples (SM-like case and leptophobic case). For  $\text{Br}(H \rightarrow ZZ)$ , we use the SM value for a given  $m_H$ :  $\text{Br}(H \rightarrow ZZ) \simeq 0.26$  (for  $m_H = 200$  GeV), 0.31 (for  $m_H = 300$  GeV). In these examples, a  $Z' \rightarrow 3Z$  branching fraction of order 1% is achievable.

We impose the following cuts: (i) pick the 6 highest  $p_T$  leptons ( $\ell = e, \mu$ ), (ii) require  $p_T > 15$  GeV and  $|\eta| < 2.4$  for each  $\ell$ , (iii) require the  $6\ell$  to be 3 pairs of light OSSF ( $\ell\bar{\ell}$ ), each of which satisfies  $|m_{\text{inv}}(\ell\bar{\ell}) - M_{Z'}| < 4\Gamma_{Z'}$ .

Irreducible backgrounds to the 6-lepton resonance from  $Z' \rightarrow ZZZ$  are negligibly small, so we only require 5 events after the above cuts to claim discovery.

Figure 2 (c) shows the luminosity needed for the discovery at the LHC with the design energy  $\sqrt{s} = 14$  TeV. The rather large required luminosity for  $M_{Z'} \sim 400$  GeV in the  $m_H = 300$  GeV case is due to the small  $\text{Br}(Z' \rightarrow$

$ZH$ ), as Figure 2 (b) shows. In the leptophobic case with  $m_H = 200$ -300 GeV, the required luminosity for 5 events after the cuts is about  $L \approx 60 \text{ fb}^{-1}$  for  $M_{Z'} = 600$  GeV, and  $L \approx 110$ -170  $\text{fb}^{-1}$  for  $M_{Z'} = 800$  GeV. The LHC design luminosity is of this order over 1-2 years of running; also six-lepton events from the ATLAS and CMS experiments can be combined since the signal is background-free.

Therefore, it is possible to have such a signal at the LHC, which can (i) tell whether the Higgs doublet has a  $U(1)'$  charge, (ii) detect a leptophobic  $Z'$ , and (iii) improve the study of the Higgs sector when combined with conventional Higgs search channels[42]. Adding other channels, such as  $Z' \rightarrow ZZZ \rightarrow 4\ell + 2j$ , would increase the reach.

Figure 3 (a) shows the reconstruction of the  $Z'$  resonance from 6 leptons for  $M_{Z'} = 800$  GeV and  $\Gamma_{Z'} = 16.6$  GeV for an arbitrary number of events in the leptophobic case.

If the number of events is sufficiently large, a Dalitz plot can reveal the resonance in the 3-body decay. We identify 3 OSSF dilepton pairs, each of which is from a  $Z$  (at the risk of rare but possible wrong combinations). Figure 3 (c) shows a relevant Dalitz plot[43]. Each axis is the invariant mass of two  $Z$ 's. The scatter plot shows a peak density at  $m_{\text{inv}}(ZZ) = m_H$  from  $H \rightarrow ZZ$ , and reveals the Higgs mass at  $m_H = 300$  GeV.

The Higgs boson can then be reconstructed, as in Figure 3 (b), by choosing 2 OSSF lepton pairs from the 6-lepton events whose invariant mass  $m_{\text{inv}}(4\ell)$  is closest to the Higgs mass, while maintaining the condition of three  $Z$  pole resonances.

If a 6-lepton resonance is found and the corresponding dilepton resonance is not found, the LEP constraint of  $\alpha_{Z-Z'}$  would suggest that the Higgs structure may be more complicated than two Higgs doublets and singlets. For example, in the two models illustrated above  $\alpha_{Z-Z'}$  would be too large unless  $M_{Z'} \gtrsim 2$  TeV. This difficulty could be eliminated if there were a separate Higgs doublet dedicated for the lepton sector (e.g., Ref. [33]).

*Summary and Outlook:* A TeV scale  $Z'$  is well motivated and closely related to the Higgs physics. The 6-lepton resonance search should be performed independent of the dilepton  $Z'$  search (even for the mass range excluded by the dilepton search). A resonance of 6 light leptons ( $e, \mu$ ) from  $Z' \rightarrow ZZZ$  is effectively background-free, and is an excellent channel to search for a leptophobic  $Z'$  without any ambiguity from the missing energy and jet misidentification. Its discovery at the LHC would imply the existence of a Higgs boson with a significant  $U(1)'$  charge in the mass range  $2M_Z \lesssim m_H \lesssim M_{Z'} - M_Z$ .

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- [34] The exact condition depends on the details of the Higgs sector. When there are two Higgs doublets, e.g.,  $\alpha_{Z-Z'} = \frac{1}{2} \arctan [g_Z g_{Z'} (z[H_d]v_d^2 - z[H_u]v_u^2) / (M_Z^2 - M_{Z'}^2)]$ . The LEP constraint can be satisfied for small  $M_{Z'}$  when  $v_u^2/v_d^2 \sim z[H_d]/z[H_u]$  holds.
- [35] For a discussion of  $ZZZ$  production from an axial vector meson in a walking technicolor model, see Ref. [24].
- [36] For models that include  $SU(2)$  singlet scalars  $S$  to break  $U(1)'$  symmetry spontaneously, there can be mixing between the  $H$  and  $S$  through  $H^\dagger H S^\dagger S$ , which can modify the Higgs coupling even for the single Higgs doublet case. However, we neglect this mixing effect in this Letter.
- [37] This is to be compared with the 4-lepton  $Z'$  resonance, where the  $Z'$  decays to a sneutrino pair (SUSY search channel) [26]. It requires a leptonic coupling, and the dilepton  $Z'$  resonance is unavoidable.
- [38] For the details of this model, which contains a  $B_3$  residual discrete symmetry, see Refs. [27, 28]. Though we chose zero charge for the leptons for the illustration, it is possible to assign small yet nonvanishing  $U(1)'$  charges from a hypercharge shift.
- [39] In the decoupling limit with  $v_u \gg v_d$ , there would not be much mixing between  $H_u$  and  $H_d$ .
- [40] It is also possible to have suppressed couplings of the  $Z'$  (KK mode of a neutral gauge boson) to the light leptons in warped extra dimension models, due to the small profile overlap. (For example, see Ref. [29].)
- [41] We use the detector parameters for CMS including (i) 70 cells for  $\eta$  and  $\phi$  in the calorimeter, (ii) a width 0.087 for the  $\eta$  and  $\phi$  calorimeter cells, (iii)  $\Delta E/E = 0.01 + 0.03\sqrt{E}$  for the electromagnetic calorimeter resolution.
- [42] For  $m_H > 2M_Z$ , the SM-Higgs can be produced via gluon-gluon or vector boson fusion processes and decay to  $ZZ$  and  $WW$ . It is discoverable at the LHC with  $L \sim \mathcal{O}(10) \text{ fb}^{-1}$  unless unnaturally heavy. (See, e.g. Ref. [32].)
- [43] An additional Higgs with a different mass may alter the plots.